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Evaluation of the Perforation Capability of a Rod Projectile as a Function of Impact Velocity

[Unclassified Title]

JAY R. BAKER

Plasma Physics Division

October 1974

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(U) This study assesses the target perforation capability of rod projectiles. A survey of published data and theoretical analyses revealed that experimental data was particularly lacking in the velocity regime of primary interest (6000 to 12,000 ft/sec) for the case of target perforation where the residual rod has a significant velocity loss. A one-dimensional cratering theory linked to an empirical correlation of the limit perforation condition is proposed for analyzing a steel rod perforating a

(Abstract continues)

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20. (Continued Abstract)

target. This analysis permits conclusions to be drawn regarding the terminal ballistics advantages obtained by increased impact velocity.

(U) CONTENTS

EVALUATION OF THE PERFORATION CAPABILITY OF A ROD PROJECTILE AS A FUNCTION OF IMPACT VELOCITY (U)

I. (U) INTRODUCTION

(U) The purpose of this study is to evaluate the potential advantages, if any, to be derived from rod projectile impact velocities above conventional values of 2000 to 3000 ft/sec. In particular this section is directed to the terminal ballistics aspect of the problem and uses the perforation of a flat plate as the measure of impact damage. The impact velocities of primary interest are in the range of 6000 to 12,000 ft/sec. Since this study did not include an experimental effort and since almost all existing data was either above or below this velocity range, it was necessary to make certain extrapolations and estimates in the course of the analysis.

(U) The credibility of such estimates can be enhanced if they are based on some theoretical model which has been verified experimentally. An extension of that model beyond the region of experimental data is then more readily justified than would be a mere extrapolation of graphical trends. In order to accomplish this for target perforation by rod projectiles, use was first made of target cratering by rods for which a well developed experimentally verified theoretical model exists which could be suitable for extrapolation to the region of interest. Making certain assumptions, an attempt is made to link the cratering model to the perforation process and thereby to obtain the desired estimates.

II. (U) ROD STABILITY DURING IMPACT

(U) Before getting into the primary concerns of rod cratering and target perforation, brief consideration will be given to the question of rod stability during impact. The phenomenon of rod instability or buckling has been studied primarily for aluminum rods at very low velocity (less than 500 ft/sec) where it is most easily obtained and where little or no target penetration occurs. The principal theoretical analysis of buckling has been done by Abrahamson and Goodier (Reference 1) with interpretation and application by Wright (Reference 2) to bearcat steel rods.

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(U) The buckling is treated as an instability that arises in an infinite rod either from an initial displacement of the rod with no displacement velocity or from a displacement velocity with no initial displacement. The time for the displacement to grow to the point of instability is calculated. Whether a rod actually becomes unstable (buckles) or not is determined by comparing the time for growth of the instability (Reference 1) with the time for release of the forces driving the instability either by perforation of the target plate τ_p or by arrival of a rarefraction wave from the back of the rod τ_R, see Table 1.

(U) Table 1, Rod Instability Criteria

$\tau_R \backslash \tau_p$	0 - 3	3 - 6	6 - 9	> 9
0-3	stable	stable	stable	stable
3-6	stable	stable	stable	marginal
6-9	stable	stable	marginal	marginal if $\tau_p < 2\ \tau_R$ unstable if $\tau_p > 2\ \tau_R$
>9	stable	marginal	marginal	unstable

The nondimensional time parameter τ_R is given by $8\ \sigma_y\ (\ell/d)/\sqrt{E_h E_e}$ and τ_p by $4\ \sigma_y (t/d)(E_h\ v_m/c_p)$ where σ_y is the yield strength of the rod material, E_h is the strain hardening bar modulus of the rod, E_e is the elastic bar modulus of the rod, v_m is the average rod velocity during perforation, c_p is the plastic wave speed in the rod $(=\sqrt{E_h/\rho})$, ℓ/d is the length to diameter ratio of the rod, and t/d is the target thickness to rod diameter ratio. A graphical presentation of Table 1 for bearcat steel is shown in Figure 1. It can be seen from this that for the velocities of interest, i.e., $v_o \sim 3$ km/sec, assuming $v_m = v_o/2$ then since for bearcat steel $c_p = 0.78$ km/sec hence $v_m/c_p \sim 2$ consequently the target must be very thick, $t/d > 10$ and/or the rods very long, $\ell/d > 23$, before it seems likely that buckling during impact will be a significant problem. Conversely for steel rods with $\ell/d < 15$ there seems to be little likelihood of buckling.

III.(U) TARGET CRATERING

(U) The cratering or penetration process of solid targets by solid rods can be modeled theoretically by using a modified Bernoulli equation of the form

$$\tfrac{1}{2}\rho_1(v-u)^2+Y = \tfrac{1}{2}\rho_2 u^2+R \qquad \text{(Tate, Ref. 3 and 4)} \quad (1)$$

or

$$\tfrac{1}{2}\rho_1(v-u)^2+K_1(v-u)^2 = \tfrac{1}{2}\rho_2 u^2+\varpi_0+K_2 u^2 \qquad \text{(Rogers, Ref. 5, 6)} \quad (2)$$

where ρ_1 is the rod density, ρ_2 is the target density, v is the impact velocity and u is the velocity of the interface between the two materials. The other terms, Y and R for Equation (1) and K_1 and K_2 and ϖ_0 for Equation (2) are effective resistance to flow terms which are related to the inertia and strength of the materials. The difference between these two modification is that for Equation (1) the flow resistances are constants while for Equation (2) they are functions of the flow velocity. While an attempt is made to relate these parameters to measureable material properties, such as yield strength for Y, in actual application they are merely adjusted so as to obtain the best possible fit to the depth of penetration and residual rod length data (Figure 2).

(U) Along with the modified Bernoulli equation go the following equations of motion:

$$dp = u\ dt \qquad (3)$$

$$d\ell = (u-v)\ dt \qquad (4)$$

$$Y = \rho_1 \ell \frac{dv}{dt} \text{ (with Equation)(1)} \qquad (5)$$

where p is the depth of penetration, ℓ is the rod length and t is time. Solving these equations produces curves such as those shown in Figure 2 which provide the dependence of final depth of penetration and residual rod length as a function of impact velocity which is exactly the kind of result needed for the extrapolation it is desired to make.

(U) It should be noted that the above crater analysis is a purely one dimensional steady state situation and that in the limit of large velocity the crater depth is independent of velocity and is given by $\sqrt{\rho_1/\rho_2}$ for Equation (1) or by $\sqrt{(\rho_1+2K_1)/(\rho_2+2K_2)}$ for Equation (2). The experimental

data suggests that this is not in fact the case but that penetration depth at very high velocities continues to increase with velocity (Reference 7). This may perhaps be attributable to two-dimensional non-steady effects which also produce the observed dependence of the crater diameter on impact velocity (Figure 3). The curve in Figure 3 is of the following form which is adapted from the results in References 8 and 9

$$\frac{D}{d} = 1 + \sigma_\infty v[1- \frac{v_c}{v} (1-e^{-v/v_c})] \qquad (6)$$

or

$$\frac{D}{d} = 1 + \sigma_\infty v \text{ (for } v >> v_c) \qquad (7)$$

A modification of the one-dimensional result which incorporates this observation can be obtained by assuming that all but the last diameter of rod length is consumed in the steady-state mode but that the last diameter of length is consumed in the non-steady formation of a hemispherical bottom to the crater. This assumption, which strictly speaking may only apply when the rod is totally consumed by the crater formation, is consistent with the observed experimental results. This modification can be expressed mathematically by replacing the hydrodynamic penetration limit of $\sqrt{\rho_1/\rho_2}(\ell/d)$ with the equation

$$\frac{p}{\ell} = \sqrt{\frac{\rho_1}{\rho_2}}(\frac{\ell}{d} -1) + \frac{1}{2} \frac{D}{d} \qquad (8)$$

Then using Equation (7) and rearranging Equation (8) gives

$$\frac{p}{\ell} = \sqrt{\frac{\rho_1}{\rho_2}} (1 + \alpha) \qquad (9)$$

where

$$\alpha = [\sqrt{\rho_2/\rho_1}(1 + \sigma_\infty v)/2-1]/(\ell/d) \qquad (10)$$

The corresponding modification of the Bernolli equation is to add a term of the form $\frac{1}{2} \xi u^2$, somewhat like the modification in Equation (2), so that

$$\frac{1}{2} \rho_1 (v-u)^2 + \sigma_1 = \frac{1}{2} \rho_2 u^2 + \frac{1}{2} \xi u^2 + \sigma_2 \qquad (11)$$

where

$$\xi = \rho_2 [\frac{1}{(1+\alpha)^2} - 1] \qquad (12)$$

and σ_1 and σ_2 are effective flow resistances corresponding to Y and R in Equation (1). Note that the parameter ξ involves material properties of both the target and the projectile through ρ_1, ρ_2 and σ_∞ and also depends on the rod length, ℓ/d.

(U) A comparison between the results of Equation (1) and those of Equation (11) for a steel rod impacting an aluminum target are shown in Figure 4. It can be seen that the modification in Equation (11) has little effect on the residual rod length. Furthermore it can be seen that for this particular case at velocities below 3 km/sec where there is some residual rod length, the effect on the penetration depth is minimal whereas above 3 km/sec the divergence between the two results increases steadily with increasing velocity. The results of Equation (11) are therefore exactly as desired and are more nearly in accord with the experimental results (Reference 7) than those of either Equation (1) or (2).

IV. (C) TARGET PERFORATION

(U) For a target of finite thickness, if the rod is of sufficient length and has sufficient velocity, it will perforate the target. This perforation phenomenon can be grouped into two regions as a function of velocity. The first is full perforation where the conditions of impact greatly exceed the minimum requirements for perforation so that there is some residual rod behind the target and its velocity is essentially the same as it was before impact. The second region is a transition perforation where the conditions exceed the minimum requirements but the residual rod has a velocity significantly below the impact velocity. For any impact configuration, the second region is bounded by a limiting impact velocity below which any residual rod has zero velocity.

(U) The first region, referred to as full perforation, has been extensively examined and a sufficiently good mathematical model exists with which to make reasonable estimates involving realistic targets (References 9 and 10). Most of the work done in that study was performed with impact velocities of 15,000 ft/sec or more. A few experiments, primarily for aluminum rods and targets, were performed at velocities down to 3000 ft/sec. While some significant deviation from the final mathematical model was observed at the lowest velocities, nevertheless the data shows that in the region of primary interest in the

present study, 6000 to 12,000 ft/sec, that model should be entirely reliable.

(U) The condition of full perforation however is not likely to be the one desired to use against conventional targets, at least not against the final layer or component within a target structure. Therefore, while this region has been rather fully characterized, the application of that analysis to the targets of present interest will be to calculate the perforation of layers preceding the final layer of a target structure.

(C) The second region, referred to as transition perforation, has also been extensively studied, particularly at conventional velocities (below 5000 ft/sec), but has not been so thoroughly characterized (Reference 11). Considerable attention has particularly been paid to the determination of the perforation limit conditions (References 12, 13 and 14). Unfortunately a number of definitions of perforation limit are in use. The one used here, i.e., the impact velocity at which the residual rod just has zero velocity, is that used in Reference 11. References 11 and 13 show that the limit velocity can be related empirically to the impact configuration by the equation (Figure 5).

$$v_L = \frac{a(t \sec \theta/d)^b}{\sqrt{\ell/d}} \qquad (13)$$

where θ is the angle between the projectile velocity and the normal to the target, and a and b are empirical constants which depend on the rod and target materials. For steel into steel and for v_L in km/sec, a ranges between 1.10 and 1.14 depending on material hardness and b is 0.8. In addition Reference 11 presents data relating the residual velocity of the rod v_R to the impact (striking) velocity v_S (Figure 6). This data can be fitted by an equation of the form

$$\frac{v_R}{v_L} = \frac{v_S}{v_L} - \exp[-\alpha(\frac{v_S}{v_L} - 1)^\beta] \qquad (14)$$

where α and β are empirical constants which for steel rods and high density rods impacting steel targets have the approximate values of 2.0 and 0.39 respectively. Other

correlations have also been proposed for residual velocity (References 11, 14, 15).

(U)The other parameter of interest in the perforation process is the mass of the residual rod. There appears to be a disparity between the behavior of hard steel rods (Figure 7) and soft ones (Figure 8) which, along with a sparsity of data, has made any generalized mathematical correlation unattainable. A purely analytical model has recently been proposed (Reference 16) for calculating the residual rod mass under the assumption of target plugging and no velocity loss in the rod. If the latter limitation could be removed this model might be a useful beginning for an analysis of residual mass in the lower velocity regime.

(U) The extrapolation of the existing data base into the 6000 to 12,000 ft/sec region can be seen from Equation (14) to depend on a determination of the limit velocity. A simple extrapolation of Equation (13) is not judged to be acceptable as will be discussed below. It is in an attempt to construct a mathematical model of the limit perforation condition that the previously discussed cratering model is utilized.

V.(C) LIMIT PERFORATION MODEL

(U) The proposed model for calculating the limit perforation thickness t_L of a target is illustrated in Figure 9. This thickness is such that for a given rod impacting at a limit velocity v_L the target is just perforated and any residual rod has zero velocity behind the target. Such a perforation condition is not actually obtained experimentally, rather a series of impacts at decreasing velocities is performed. These results are then extrapolated to the limit condition of zero residual rod velocity. The analytical model for calculating the limit perforation thickness t_L is based on the assumption that this thickness is directly related to the penetration depth p of the crater that would be made by the same rod impacting at the same velocity into a semi-finite target of the same material. The simplest relationship is that the limit thickness is exactly equal to the crater depth. Empirical evidence however shows that the limit thickness can be either more or less than the crater depth. The latter can occur at very low velocities or for very long

rods, where the final stage of the perforation process is at very low velocity. The equation which generalizes this relationship is

$$\frac{t_L}{d} = (1 + \epsilon) \frac{p}{d} \tag{15}$$

Note that for the case of an oblique impact, where θ is the angle between the normal to the target surface and the rod's velocity vector, the target thickness t_L/d referred to in this equation is the effective target thickness which is given by the equation

$$\frac{t}{d_{eff}} = \frac{t}{d} \sec \theta + \frac{1}{2\cot\theta} \tag{16}$$

The effective thickness given by Equation (16) is that suggested in Reference 9 and, except for the second term, which for thick targets is generally a small correction, agrees with that used in Reference 11.

(C)The parameter ϵ is most likely a function of both velocity and rod length. The crater depth p/d in Equation (15) can be obtained either from a mathematical model such as discussed in Section III or from experimental cratering data such as is presented in Figure 10 for a steel rod impacting a steel target. It should be noted that curve (1) in this figure is for a rigid rod penetration while curve (2) represents a deformable rod process. In actual practice at a sufficiently high impact velocity (in this case a little above 1.0 km/sec) the rigid rod will begin to deform and the penetration will decrease until it meets the deforming rod curve which it will then follow. For the purpose of this report, only the deforming rod curve will be used to fit the data since the desired extrapolation is from 1.5 km/sec up. Using this curve and the steel-steel limit perforation data from Reference 11, a fit for ϵ can be obtained as shown in the insert in Figure 11. The empirical equation is

$$1 + \epsilon \cong 2e^{-\ell/d/30} \tag{17}$$

The form of this equation is entirely arbitrary and, while other expressions might equally well fit the data, the important point is that the fit is particularly well defined between ℓ/d of 10 and 20, which is the region to be extrapolated, and therefore other curves would necessarily

produce essentially the same results in that region. For the limited data available above 1.2 km/sec no significant velocity dependence was detected. Figure 11 shows a comparison between Equations (15),(16) and (17) and Equation (13) and the experimental data. It can be seen that the proposed analytical model fits very well at velocities above 1.2 km/sec. Furthermore Figure 12 shows why a mere extrapolation of Equation (13), particularly beyond 3 km/sec, is possibly quite misleading. Such an extrapolatin suggests that it requires smaller and smaller increments of energy for the same rod to perforate increasingly thicker targets. Both experience and intuition support the opposite conclusion. In particular it is known that, as the velocity increases, the added energy does not go solely into the penetration process but also is consumed in the creation of a larger diameter hole. This effect is included in the proposed perforation model and hence the resultant curves indicate that increasingly more energy is required to perforate thicker targets.

(U)Equations (15), (16) and (17) and Figure 10 now permit the calculation of the limit perforation conditions for a steel-steel impact. A comparison can therefore be made between the theoretical model and two independent experimental shots.

(C)The first comparison is the limit perforation for a 105mm round with a tungsten-carbide (WC) penetrator. The penetrator mass is 2900g. The ℓ/d is 2.9 ($d = 4.4$ cm) and at 4400 ft/sec (1.34 km/sec) and 60° obliquity the experimental target thickness for limit perforation is 4.70 inches. For an oblique impact the effective target thickness is $(t/d)\sec\theta$. For $\theta = 60°$, $\sec\theta = 2$, for steel into steel at 1.34 km/sec from Figure 11, an estimate of $p/\ell = 1.0$ is obtained between the two curves. To correct for the greater density of WC, the penetration becomes

$$\frac{p}{\ell} = \sqrt{\frac{\rho_{WC}}{\rho_{steel}}}\left(\frac{p}{\ell}\right)_{steel-steel} = \sqrt{\frac{15.63}{7.83}}(1.0) = 1.413$$

Then using Equations (15), (16) and (17)

$$\frac{t}{d} = 0.5\ (1 + 0.433)(1.413)(2.9) = 2.936$$

$$t = (2.936)(4.4\text{ cm}) = 12.9\text{ cm} = 5.1\text{ in.}$$

This is to be compared to the experimental value of 4.70 in. and is within 8.5% of that value which compares very favorably.

(C) The second comparison is for a more complex target configuration. The target consists of two separated steel plates. The first is 2 in. thick and the second is 1 in. thick. The steel rod impacts at normal obliquity ($\theta = 0°$, $\sec\theta = 1.$) at a velocity of 8515 ft/sec (2.60 km/sec) and has a length of 2.81 in. and diameter of 0.32 in. ($\ell/d = 8.78$). The experimental result is that the second target was more than perforated since some residual rod embedded in a witness plate hence the impact configuration exceeds somewhat the limit perforation condition. For a complex multiple plate configuration, it is perhaps more useful to make the comparison between the calculated length of rod needed to produce a limit perforation and the length of the experimental rod.

(C)Using the analysis of Reference 9 or 10 the length lost in the first plate is

$$\frac{\Delta\ell_1}{d} = \left(\frac{t_1}{d} + \frac{\Delta t}{d} + \frac{v_T}{d}\right) = (6.25 + 0.15 + 1.08) = 7.48$$

The length required for limit perforation of the second plate is

$$\ell_2/d = (t/d)/[(1+\varepsilon)p/\ell] = 3.125/[(2e^{-\ell_2/d/30})(0.85)]$$
$$= 1.838e^{\ell/d/30} = 1.963$$

Hence the total required length is

$$\frac{\ell_T}{d} = \frac{\ell_2}{d} + \frac{\Delta\ell_1}{d} = 1.96 + 7.48 = 9.44$$

This value is greater than the experimental length by about 7.5%. Since the experiment exceeded the limit conditions, the calculated length should have been smaller than the experimental value, hence the error in the estimate is actually greater than 7.5% although probably still on the order of 10%.

(U)It is concluded therefore that the proposed limit perforation model will provide reasonable estimates of the conditions required for threshold perforation of a target

in the 6000 to 12,000 ft/sec velocity regime. In addition, it can give estimates of the residual velocity of the rod as the impact velocity rises above the threshold using Equation (14). The remaining parameter, however, the residual mass of the rod, which is of prime importance, is beyond the reach of this analysis when the perforation process is in the transition region, i.e. when the residual velocity is significantly less than the impact velocity.

VI.(C) APPLICATION OF THE LIMIT PERFORATION MODEL

(C) The limit perforation model can now be applied to a selection of hypothetical steel targets which are representative of portions of real conventional targets. The targets and impact configurations are illustrated along with the graphical results in Figures 13, 14, 15 and 16. The steel projectile mass required for limit perforation is presented as a function of velocity for selected values of ℓ/d. The results are limited to the region above 1.5 km/sec where it is reasonably certain that the rods behave in a deformable manner. It can be seen that in almost all cases, increasing the impact velocity to at least 3 km/sec significantly decreases the required projectile mass. It can be seen further that increasing the ℓ/d of the rod up to about 20 also significantly decreases the required mass. The same trend in both these parameters continues beyond those points but the additional benefit becomes marginal. Figures 17 and 18 show alternative presentations of the same data. In particular Figure 18 illustrates the relative hardness of the four targets for a given rod configuration.

(U) Although the conclusion drawn from this analysis is that higher impact velocity is a distinct advantage in so far as lesser projectile mass being required, two qualifications should be kept in mind. The first is that the analysis does not consider the need for a given size hole in the target, i.e. the curves in Figures 13 thru 16 are obtained with regard only to perforating the target. Figure 17 gives some idea of the effect on the analysis if a given diameter rod is required in order to obtain a desired hole size. It can be seen that the larger the required rod diameter, the shorter (in terms of ℓ/d) and the heavier the rod must be.

(C) The second qualification follows from the penetration behavior illustrated in Figure 10. At velocities below 1.5 km/sec a steel rod undergoes a transition to a non-deforming rigid penetrator behavior. Therefore the trends shown in Figures 13 and 18 are reversed and the required projectile mass becomes rapidly less as the transition proceeds from a deforming to a non-deforming rod. With continued decrease in velocity the mass required must then rise again in order to maintain the energy available for the penetration process. The important point is that the minimum mass required for a rigid rod may be significantly lower than that for a hypervelocity deforming rod. This comment is particularly important with regard to rods of materials other than steel where the velocity at which the transition occurs might be considerably different than for steel. Hence the judgment to increase projectile velocity can not rest solely on the results for steel rods nor even on terminal ballistics considerations alone. However if other considerations should dictate velocities greater than 1.5 km/sec (5000 ft/sec), then the analysis presented here indicates that increases up to 3 km/sec (10,000 ft/sec) is advisable at least for steel rods.

VII.(U) SUMMARY AND CONCLUSIONS

(U) A preliminary application of a low velocity buckling analysis has been made to the case of a steel rod impacting normal to the target. From this, some estimate may be made of the impact conditions under which rod buckling may be a problem. It can be concluded that for $\ell/d \leq 15$ no problem is likely to exist for the impact conditions of interest.

(U) A reasonably well established one-dimensional theoretical analytical model (requiring no extensive computer calculations) exists for cratering of solid metal targets by solid rods impacting normal to the target. Considerable data exists with regard to crater depths particularly for the materials of primary interest, i.e. steel and aluminum. Data on residual rod length and crater diameter are rather sparse although it may already exist as a result of the penetration experiments but may simply be unmeasured and/or unpublished. Additional data

would be useful for generalizing the material dependent parameters required by the cratering model. A major limitation of the cratering theory is the inability to account for two-dimensional effects involving the hole size and the consequent continued dependence of the crater depth on velocity even at very high velocities. A modification to this theory to include this effect has been proposed.

(C) A simple analytical model has also been proposed which permits the calculation of the limit perforation conditions (i.e., the residual rod has zero velocity) using either the one-dimensional cratering theory or any available crater penetration data. Calculations using this model suggest considerable advantage with respect to projectile mass by increasing both the impact velocity up to 3 km/sec and the rod length up to ℓ/d of 20. Comparison with the limited high velocity experimental data available indicates that estimates made with this model are accurate to within 10%. Furthermore the model is presently limited by an empirical parameter ϵ which has really only been evaluated for steel targets. The dependence of that factor on material and impact velocity should be more fully explored in order to properly generalize and refine the proposed model. In particular a transition to a non-deforming rod behavior should be provided at low velocities (below 1.0 km/sec for steel) so that the limit perforation thickness goes to zero as the impact velocity goes to zero. Furthermore there is a significant need for additional data in the 2 to 3 km/sec velocity regime in order to distinguish between the calculations of the proposed model and extrapolations of existing empirical correlations.

(U) For the more practical case of target perforation, where the residual rod has some residual velocity, a useable analytical model, based on extensive experimental data, is available for the condition where the target is relatively thin so that there is little or no velocity loss during the perforation process. For the case where significant velocity loss occurs, while it is possible to calculate the residual velocity if the limit velocity for that configuration can be determined, there is no empirical correlation whatever for obtaining the residual mass of the rod. This is due to the very limited systematic data that exists above 2 km/sec and to the divergence between

the behavior of ductile and brittle rods and the considerable scatter of the latter in the regime below 2 km/sec where data is available. Similarly there is little or no data that permits a correlation for hole size under those circumstances. Therefore in order to obtain an analytical model for residual rod mass and target damage under conditions of significant velocity loss, the primary requirement is a systematic experimental impact study for those conditions and for the materials and range of impact velocity of primary interest.

(U) Finally it should be pointed out that all of the preceding is directed at targets that consist of solid homogeneous flat spaced plates. While some actual targets can be adequately described by such a configuration, others, as shown in Figure 19, are exceedingly complex and cannot be. The limited applicability of any simple analytical model should be clearly borne in mind.

(U) In summary, the following conclusions regarding the terminal ballistics of metal rods impacting single layer metal targets can be made:

I. Penetration

1. Simple analytical model established requiring no extensive computer calculations.
2. Considerable penetration data exists
3. Sparse residual length and crater diameter data
4. Experimental determination of material parameters required
5. Modification of analytical model for velocity dependence needed.

II. Limit Perforation

1. Simple analytical model proposed which requires no extensive computer calculations
2. Further verification of model needed above 2 km/sec
3. Modification of model needed for thin targets and low velocity
4. Substantial experimental data exists below 1.5 km/sec.

III. Full Perforation

1. Simple analytical model for residual mass, requiring no extensive computer calculations, is available when there is little or no velocity loss
2. When significant velocity loss occurs, simple analytical model is available for residual velocity but not for residual mass
3. Limited experimental residual mass and velocity data below 2 km/sec
4. No hole size data published
5. Virtually no experimental data above 2 km/sec when significant velocity loss occurs.

(U) In order to close the existing gaps and to further extend the understanding of this area of terminal ballistics, the following further investigations are recommended:

I. Theoretical

1. Modify penetration model to include velocity dependence
2. Refine limit perforation model
3. Adapt full perforation model for conditions of significant velocity loss
4. Apply finite difference computer code simulation.

II. Experimental

1. Establish values for penetration model material parameters
2. Review existing data sources for residual length and crater diameter measurements
3. Conduct limit perforation impacts in 2-3 km/sec regime
4. Conduct full perforation impacts in 2-3 km/sec regime with significant velocity loss
5. Examine effect of alloys on material parameter values
6. Examine effect of rod alignment on impact process
7. Examine effect of complex multilayered targets .

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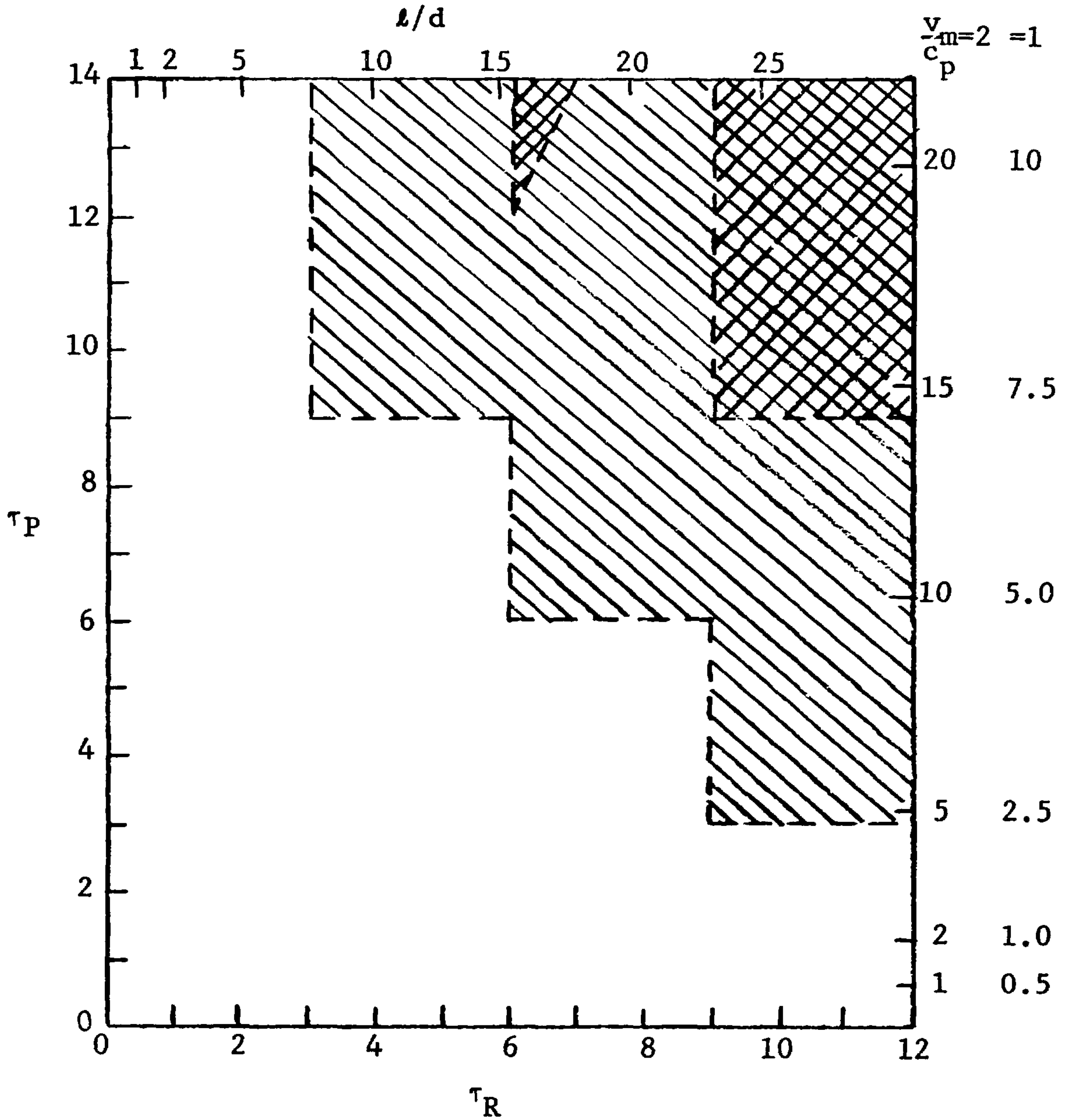


$$\tau_P = \frac{4\sigma_y (t/d)}{E_h (v_m/c_p)}$$

$$\tau_R = \frac{8\sigma_y (\ell/d)}{\sqrt{E_h E_e}}$$

For Bearcat Steel:

σ_y = 220 kpsi

E_h = 690 kpsi

E_e = 30,000 kpsi

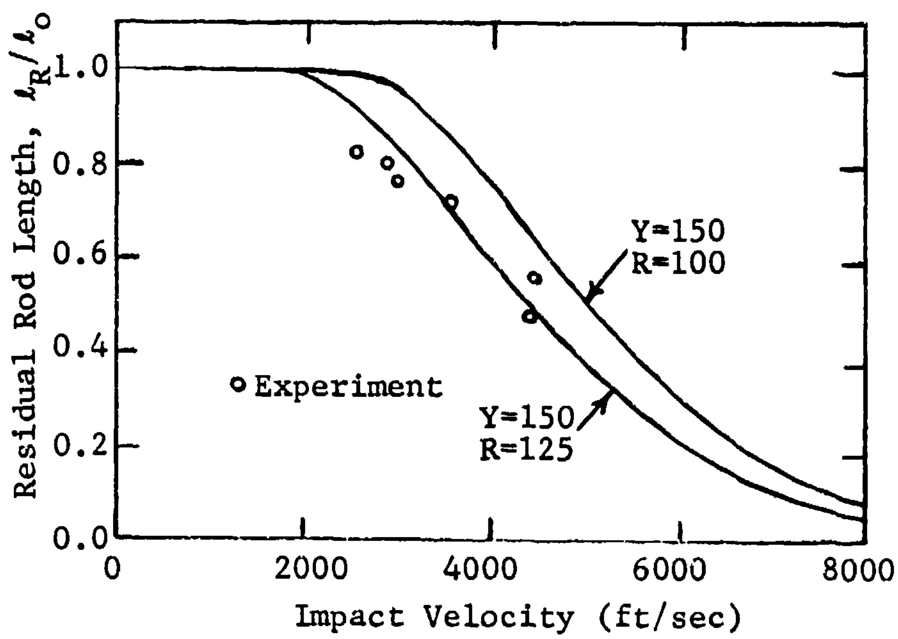
c_p = 2560 ft/sec

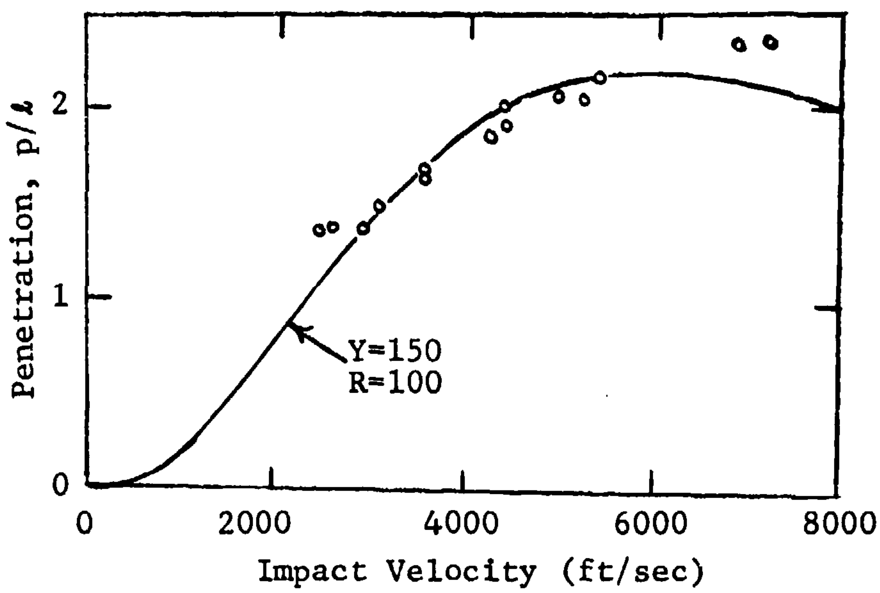
thus

$$\tau_P = 1.275 \frac{(t/d)}{(v_m/c_p)}$$

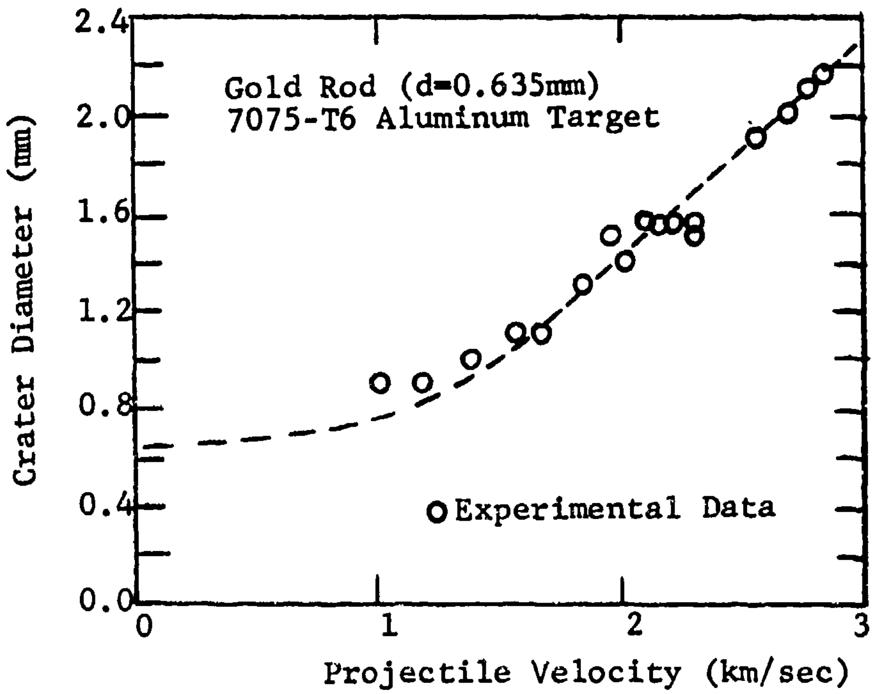
$$\tau_R = 0.387\ (\ell/d)$$

(U) Figure 1. Steel Rod Buckling Criteria (U)

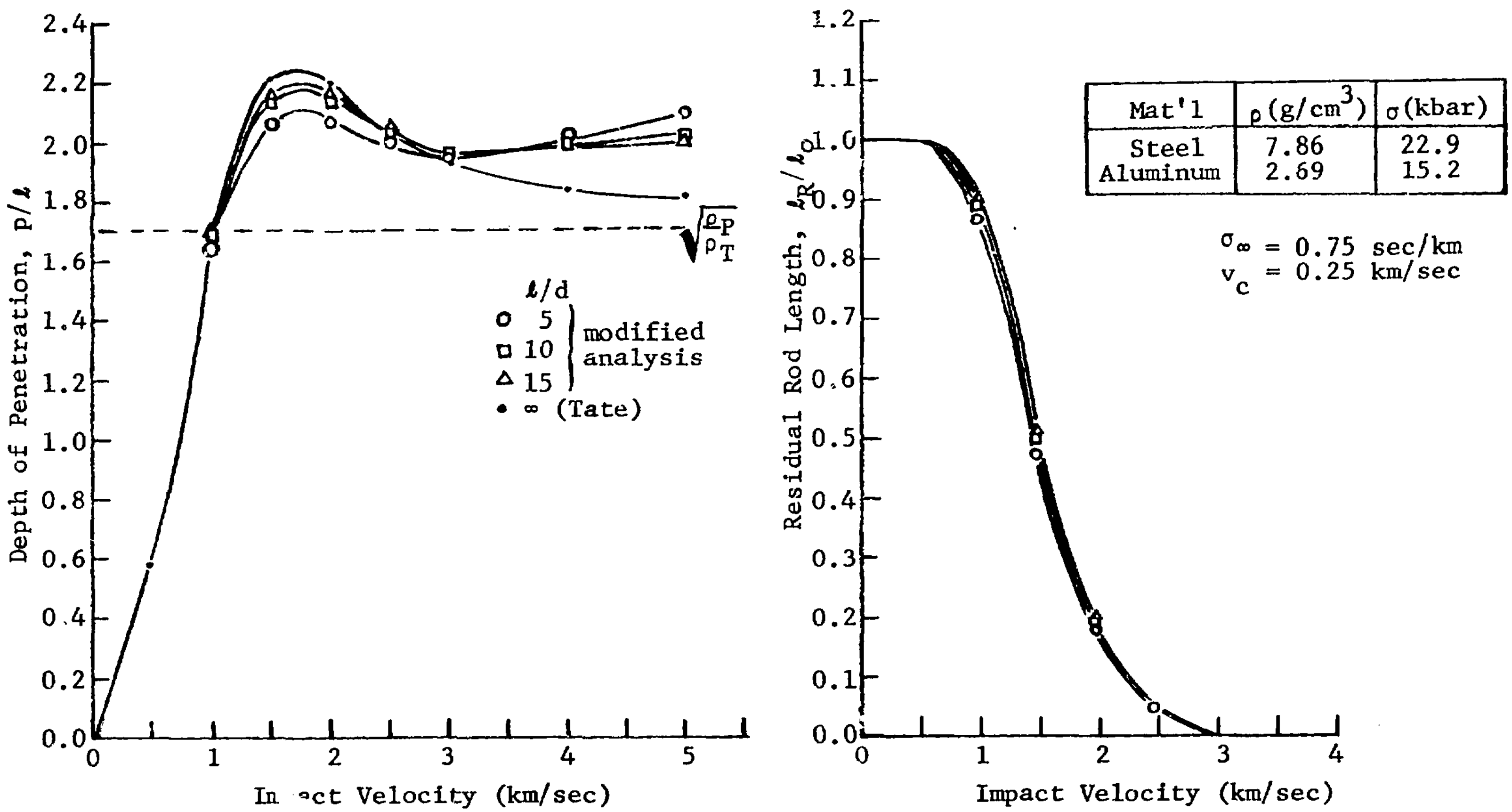




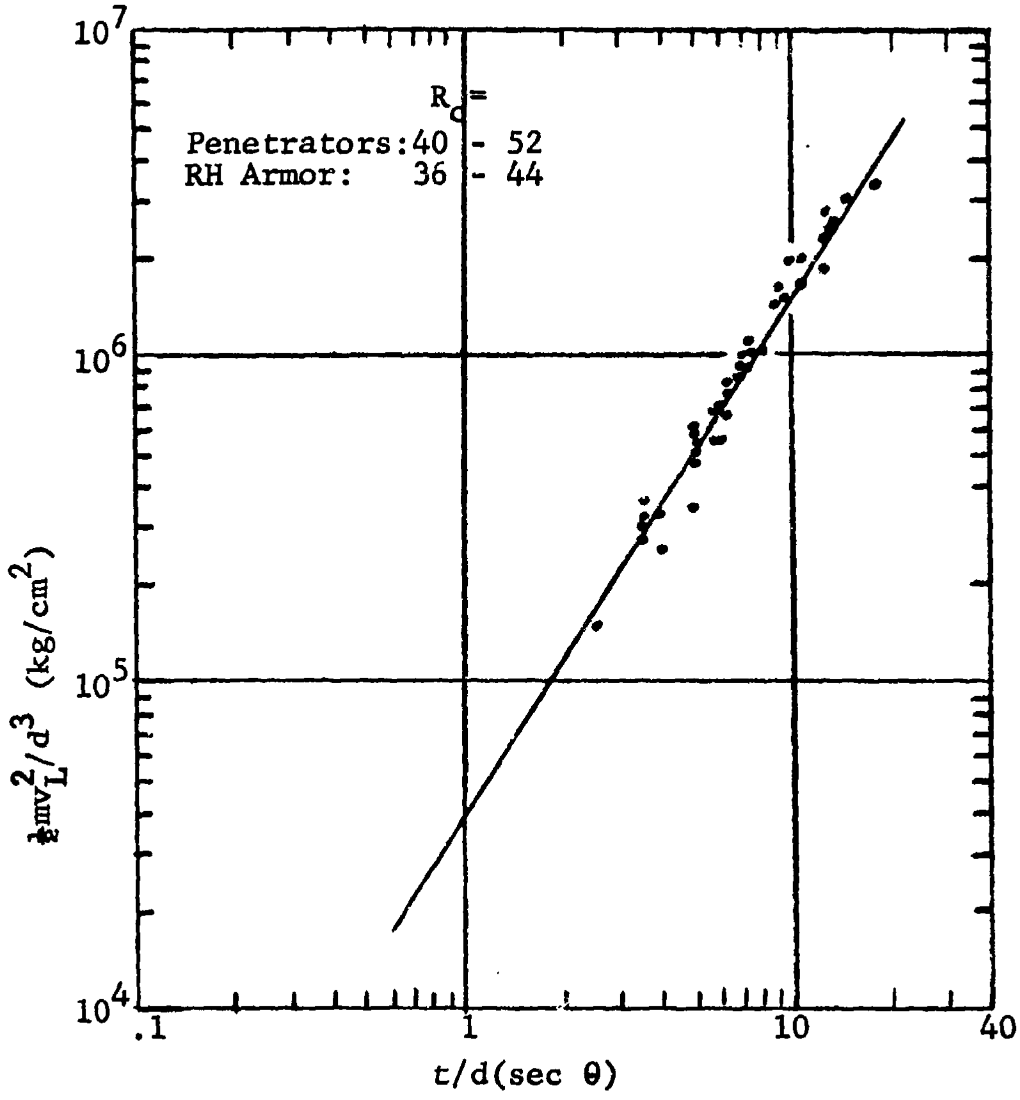
(U) Figure 2. Comparison of Rod Penetration Theory with Experimental Data for Vibrac Steel into Aluminum (from Reference 4)(U)



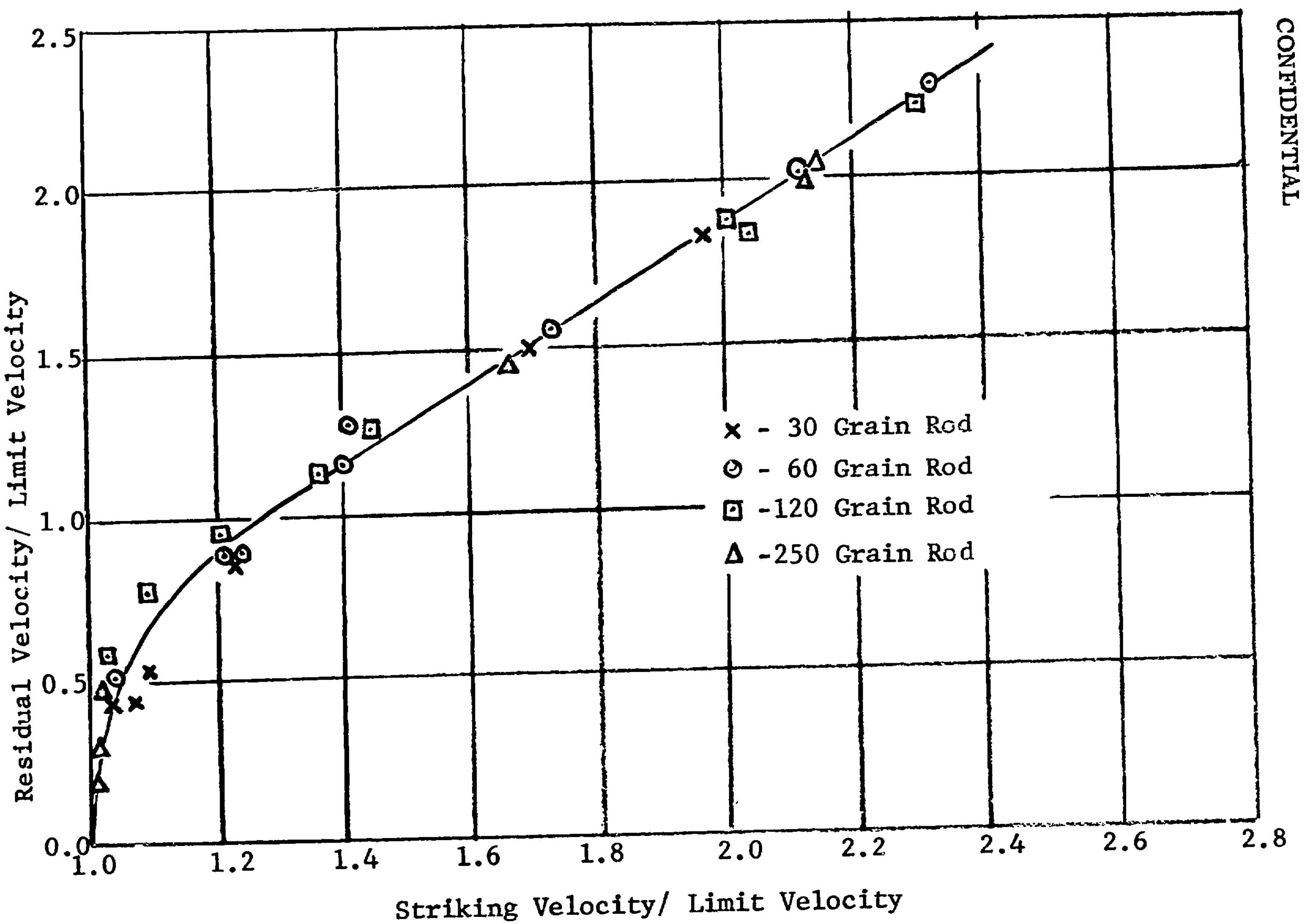
(U) Figure 3. Crater Diameter Dependence on Impact Velocity (taken from Rogers, J.W., "Deceleration of a Rod while Penetrating a Target (U)," p.235-247, NOTS TP-2958, Sept., 1962 (C))



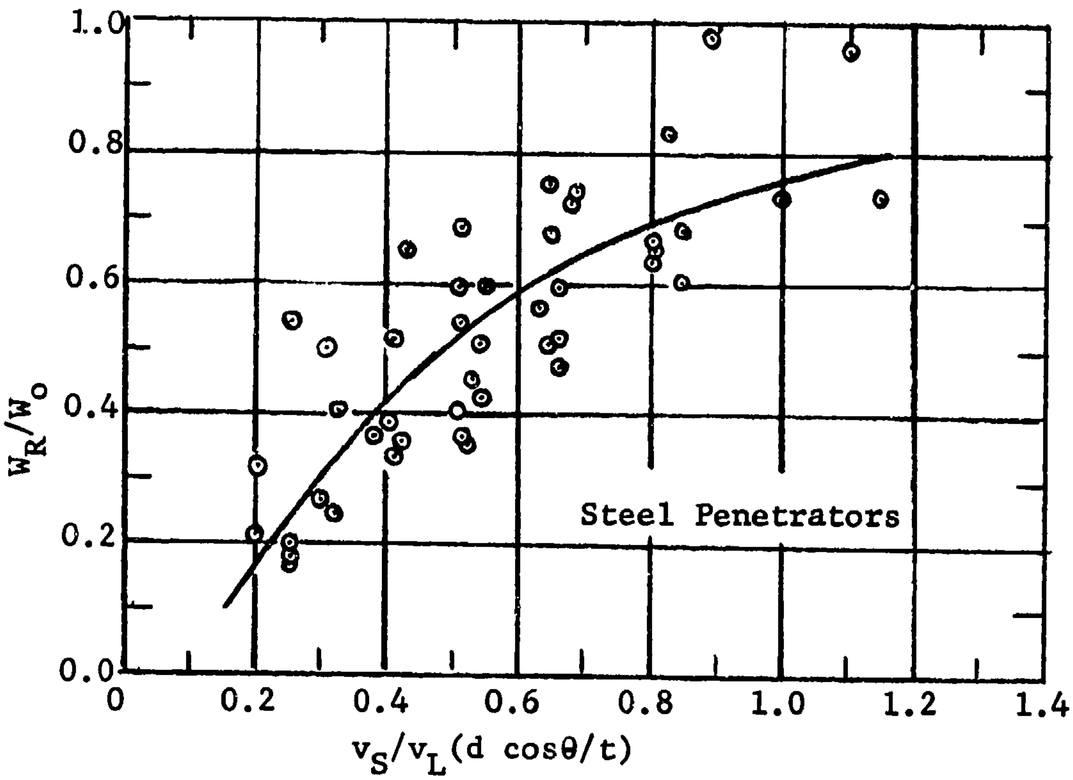
(U) Figure 4. Crater Depth and Residual Rod Length vs. Impact Velocity for a Steel Rod Impacting an Aluminum Target (U)



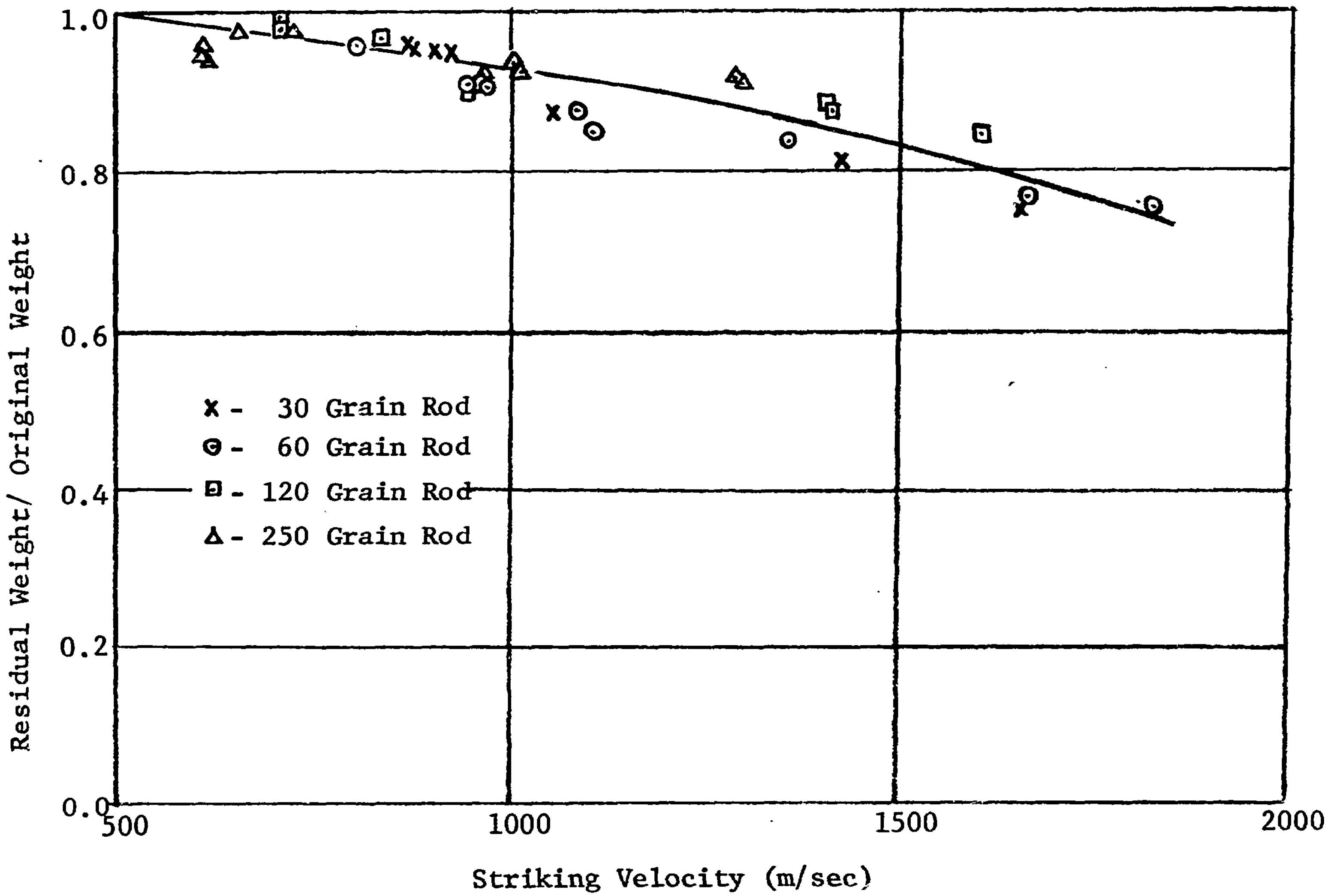
(C) Figure 5. Experimental Correlation between Limit Velocity and Impact Configuration (U) (from Reference 11)



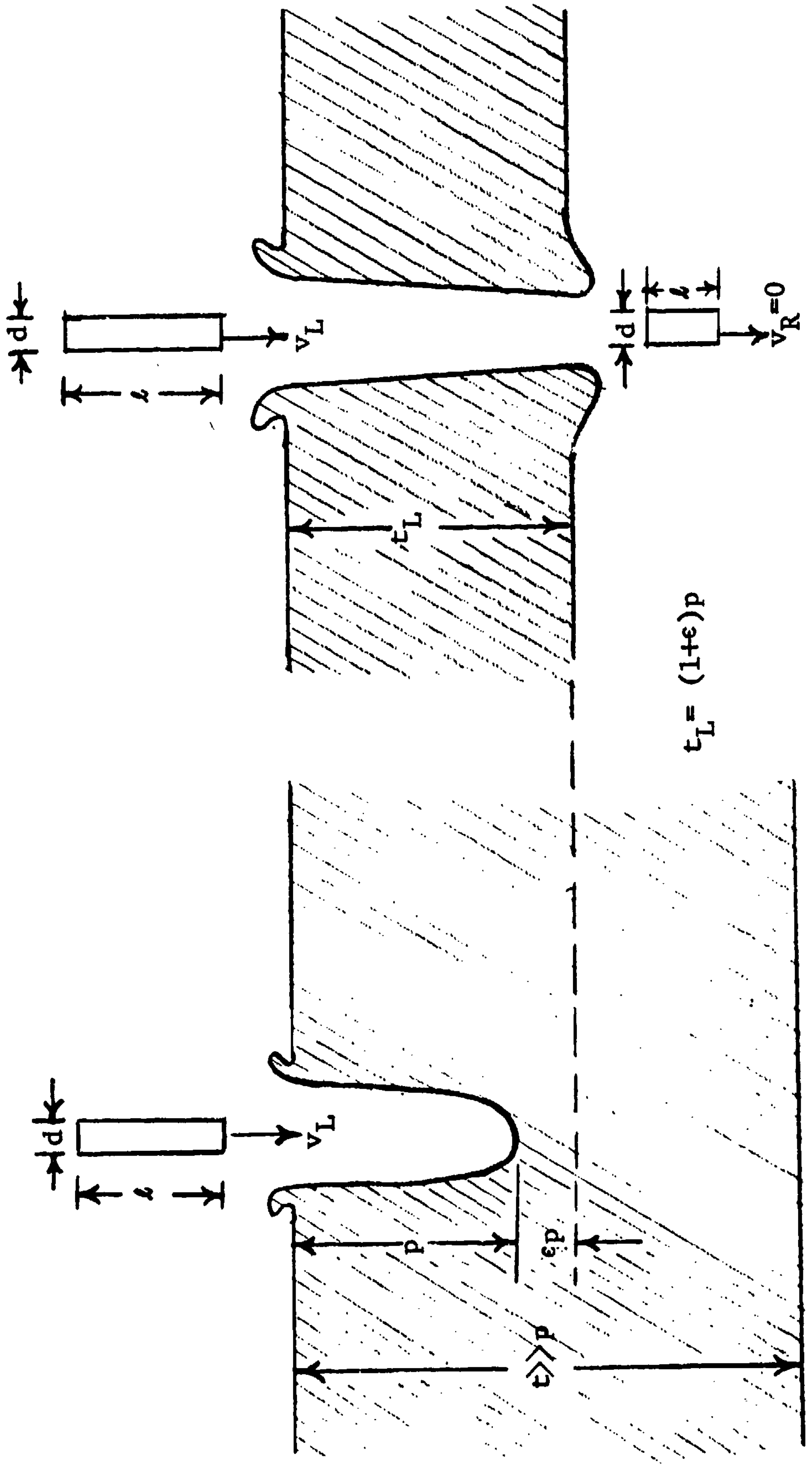
(C) Figure 6. Residual Velocity for Mild Steel Rods, $\ell/d=10$, Perforating a 6.35 mm Target of Like Material (U)
(from "Proceedings of the Army Symposium on Solid Mechanics,"1968)



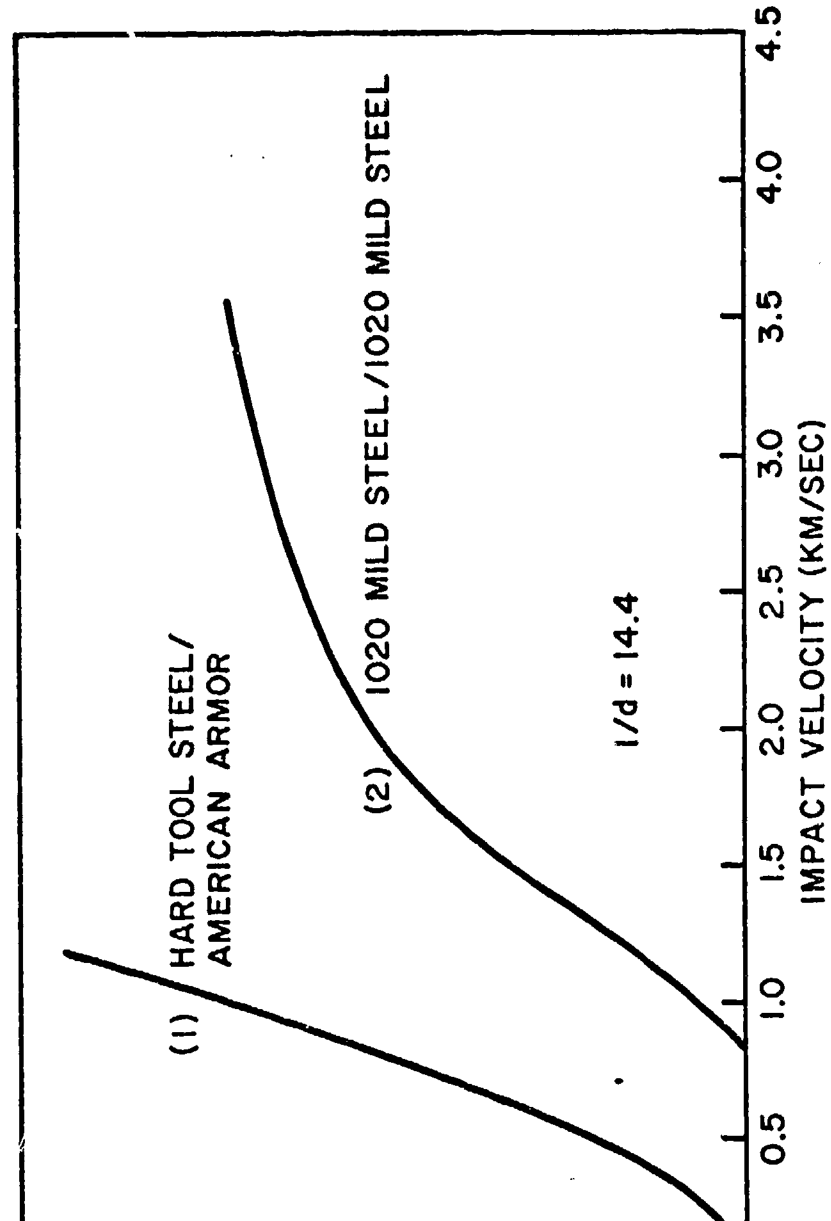
(U) Figure 7. Residual Weight of Non-shattering Penetrators into RH Armor as a Function of Velocity (U) (from Reference 11)



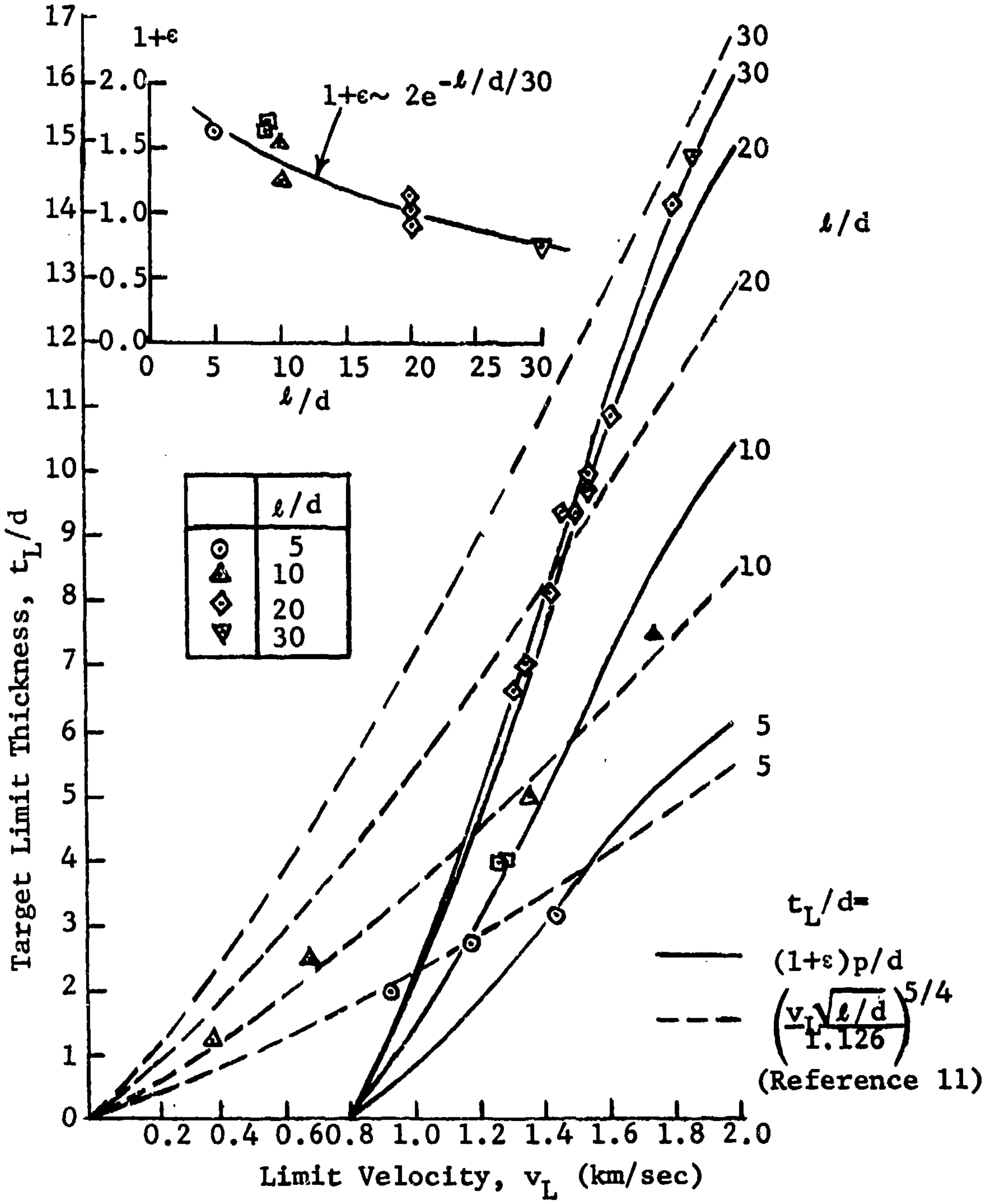
(C) Figure 8. Residual Weight to Original Weight Ratio for Mild Steel Rods, $\ell/d=10$, after Perforating a 6.35 mm Target of Like Material (U) (from "Proceedings of Army Symposium on Solid Mechanics," 1968)



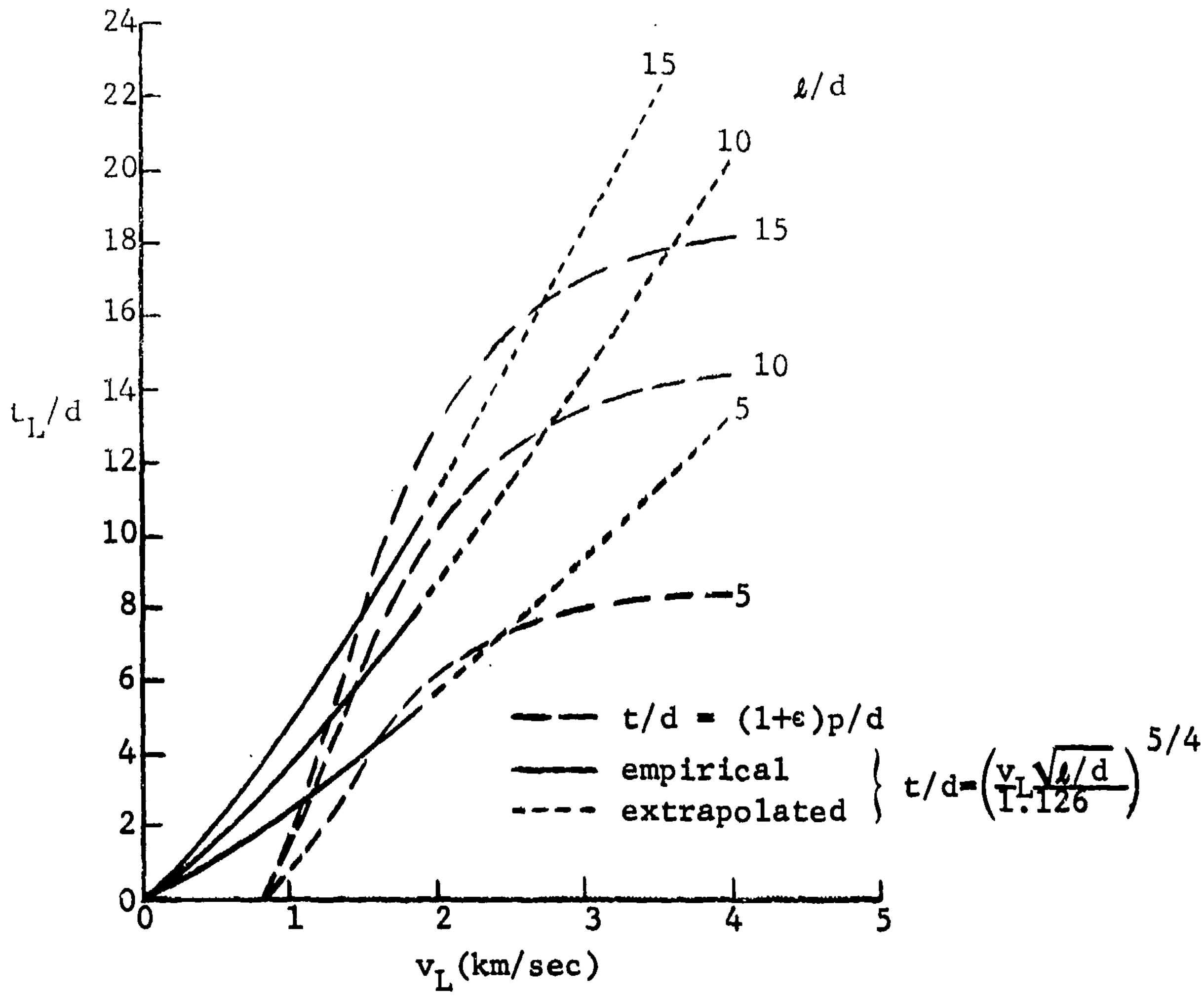
(U) Figure 9. Theoretical Model for Limit Perforation Thickness (U)



(U) Figure 10. Crater Depth vs. Impact Velocity for Hard and Soft Steel (U)
(1) from Reference 6, (2) from Reference 5

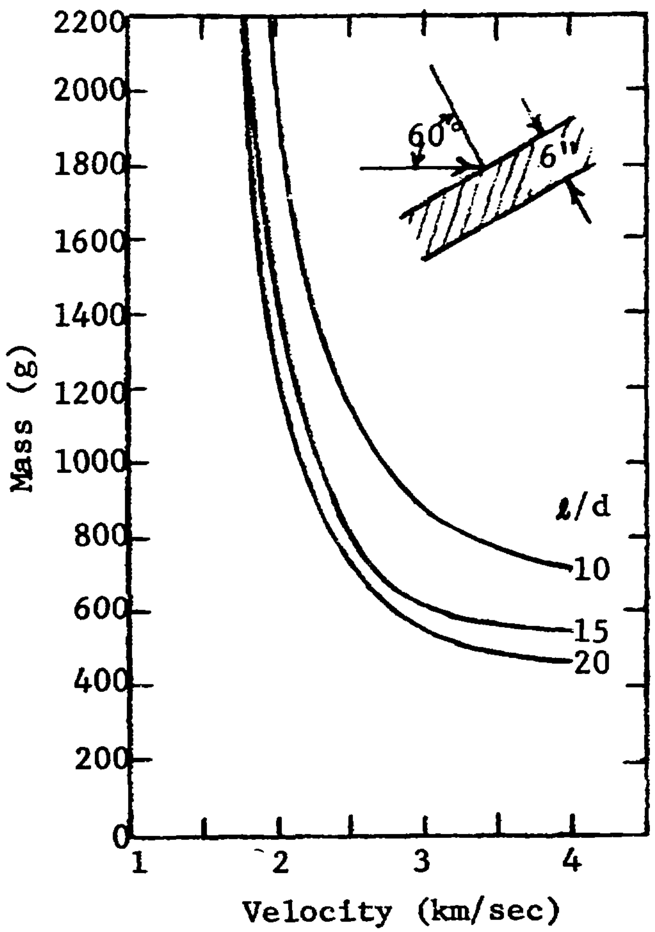


(C) Figure 11. Comparison of Perforation Limit Thickness vs. Velocity Data for Steel into Steel with Two Empirical Fits (U)



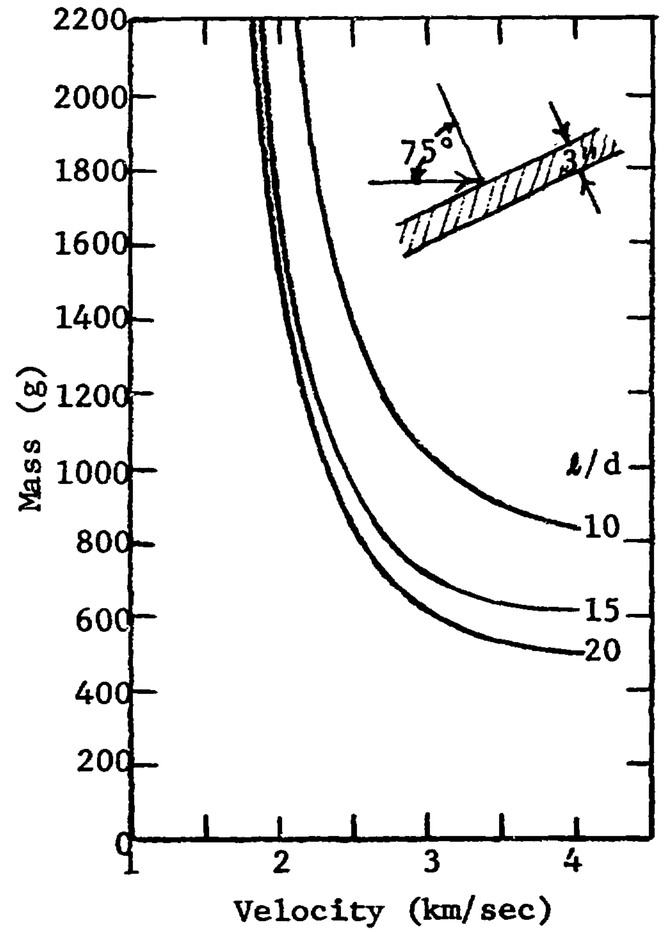
(C) Figure 12. Comparison of Extrapolation of Two Empirical Fits to Perforation Limit Thickness vs. Velocity for Steel into Steel (U)

TARGET NO. 1



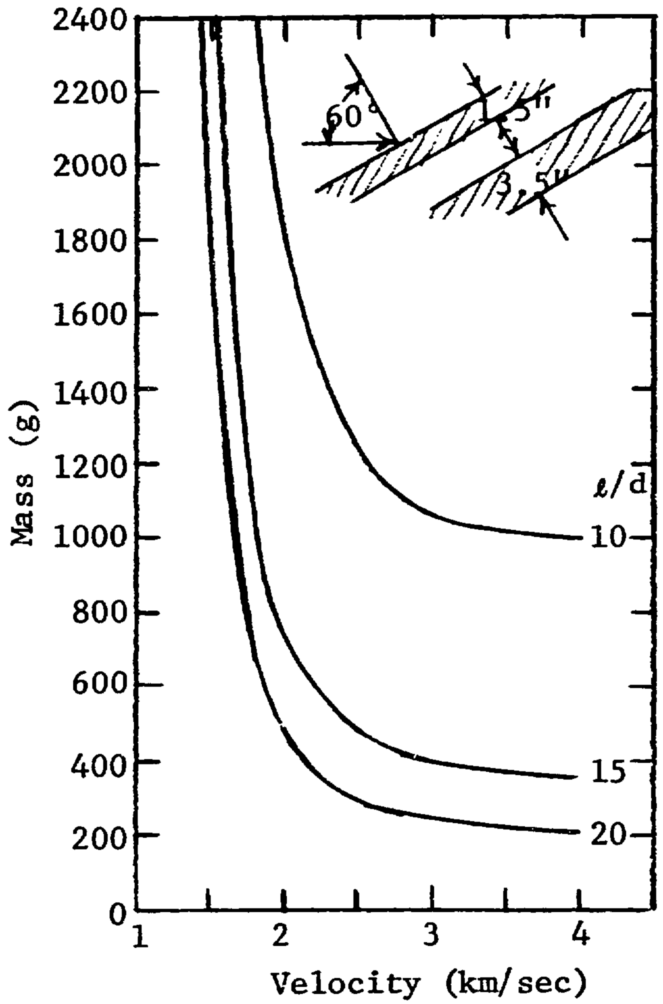
(C) Figure 13. Projectile Mass vs. Impact Velocity for a Steel Rod into Steel Target (U)

TARGET NO. 2



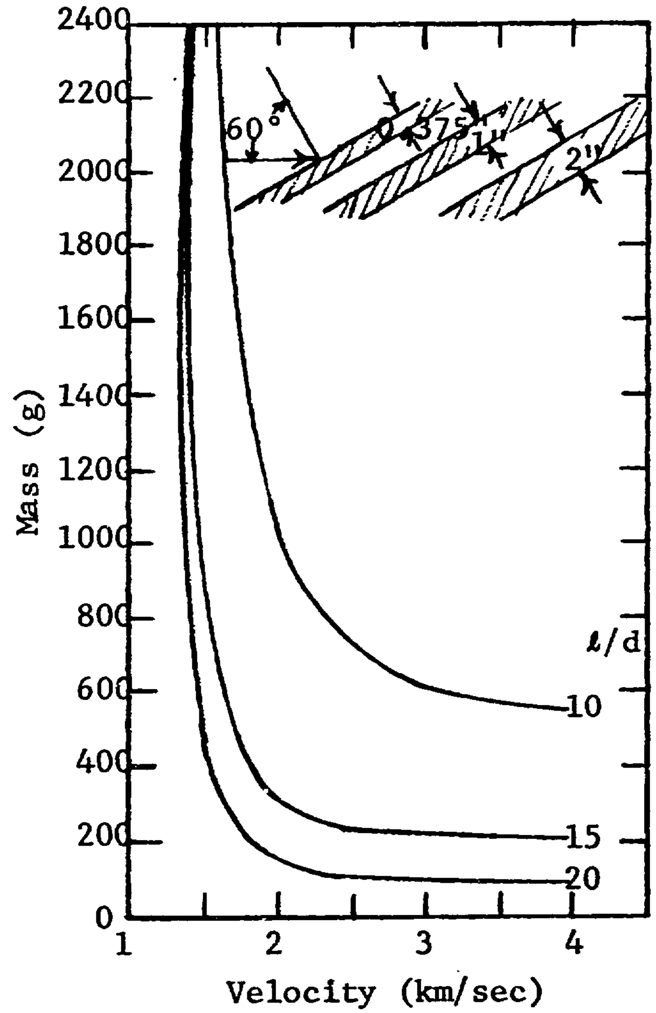
(C) Figure 14. Projectile Mass vs. Impact Velocity for a Steel Rod into Steel Target (U)

TARGET NO. 3

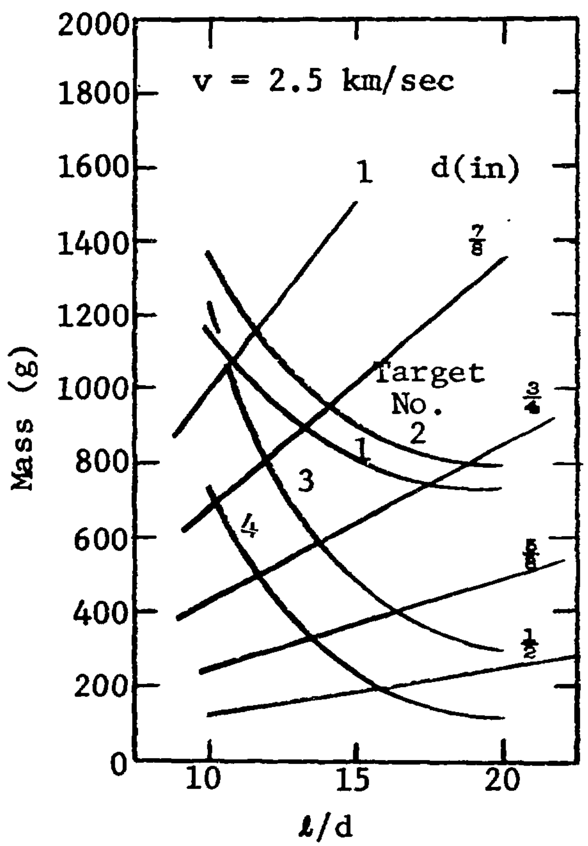


(C) Figure 15. Projectile Mass vs. Impact Velocity for a Steel Rod into a Steel Target (U)

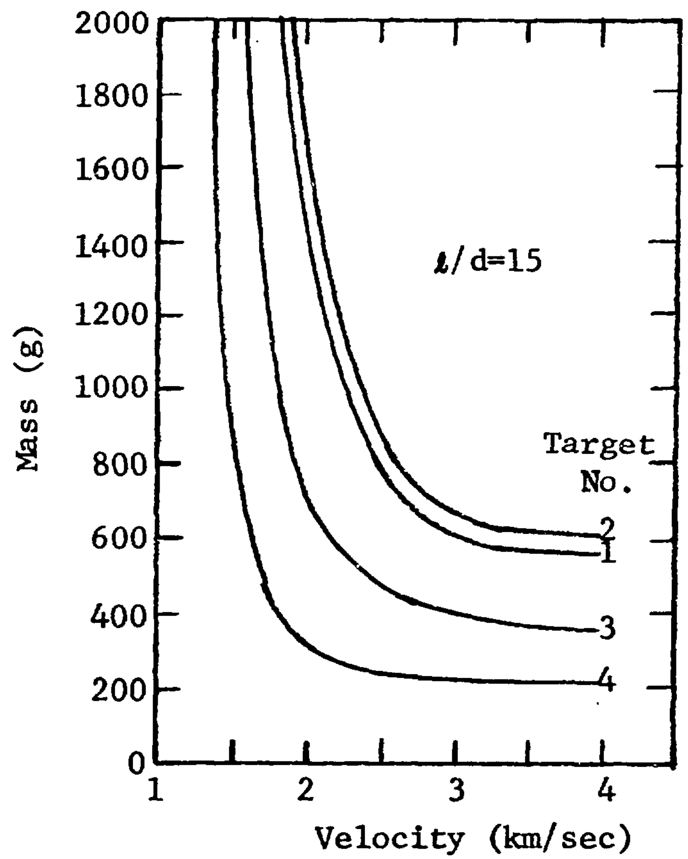
TARGET NO. 4



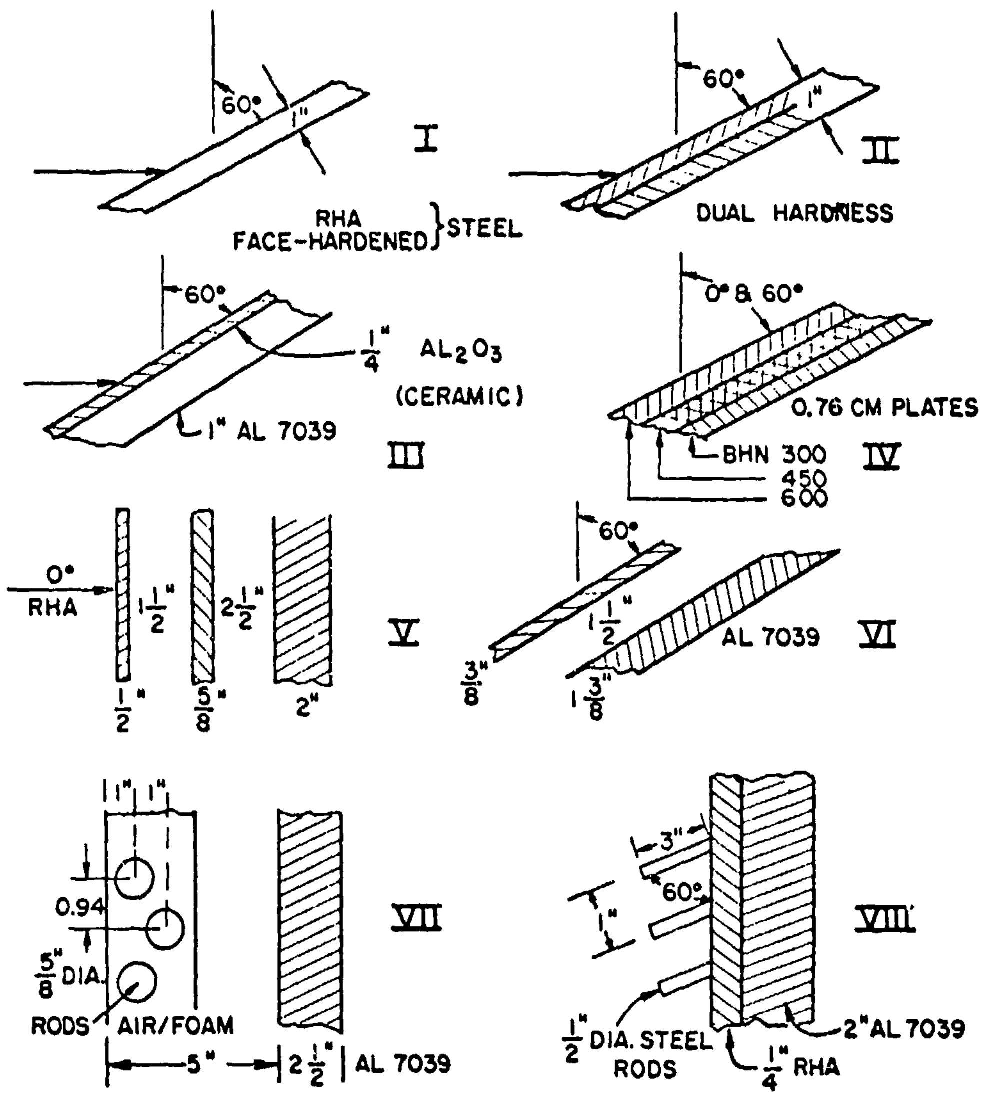
(C) Figure 16. Projectile Mass vs. Impact Velocity for a Steel Rod into a Steel Target (U)



(C) Figure 17. Projectile Mass vs. Rod Length for a Steel Rod Impacting the Four Steel Targets as Illustrated in Figures 13 thru 16 at 2.5 km/sec (U)



(C) Figure 18. Projectile Mass vs. Impact Velocity for an ℓ/d of 15 Steel Rod Impacting the Four Steel Targets as Illustrated in Figures 13 thru 16 (U)



(C) Figure 19. APC TARGET CONFIGURATIONS (U)

UNITED STATES GOVERNMENT

Memorandum

7100-017

DATE: 22 January 2004

REPLY TO ATTN OF: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REF (A) FOR DECLASSIFICATION

TO: Code 1221.1

REF: (a) "Evaluation of the Perforation Capability of a Rod Projective as a Function of Impact Velocity", Jay R. Baker, Plasma Physics Division, NRL Memo Report 2892, October 1974 (U)

1. References (a) reports on a study of the effects of a high velocity rod penetrating a metal target. No experimentation is included.

2. The technology and equipment of reference (a) have long been superseded. The current value of these papers is historical.

3. Based on the above, it is recommended that reference (a) be available with no restrictions.

Burton G. Hurdle

BURTON G. HURDLE
NRL Code 7103

CONCUR:

Edward R. Franchi 1/23/2004

E.R. Franchi Date
Superintendent, Acoustics Division

CONCUR:

Tina Smallwood 1/28/04

Tina Smallwood Date
NRL Code 1221.1